THE “GOD PARTICLE,” DARK MATTER, BLACK HOLES, AND ALL THAT[1]

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With guest appearances by Bigfoot

Abstract:

Recently, the news outlets were buzzing with excitement about the possible discovery of a new particle at the Large Hadron Collider (LHC). The LHC at CERN is not only the world's largest machine and fridge, but also home of the world’s largest international scientific collaborations, with several thousand scientists from over 100 different nations. As such, the underlying science may be of interest to linguists. This paper presents a basic overview over our current knowledge of the universe and aims at explaining the big fuss about the search for the Higgs (also known as the “God particle”) and its possible connection to dark matter. No knowledge of advanced mathematics or physics is required to read this paper. For readers who want to know more, some references and recommendations for further reading are included at the end. The talk at the ATA conference will include a summary of the latest experimental and theoretical results. The talk and these proceedings are meant to supplement and complement each other, but are otherwise independent of each other.

[1] Original contribution to the American Translators Association's 53rd Annual Conference, submitted August 2012

1 Introduction

Before delving straight into the depths of quantum theory and related topics, two disclaimers are in order:

Disclaimer 1: The Higgs particle has nothing to do with religion or faith, that is, nothing more than any other particle in the universe. The term "God particle" was coined by Nobel Prize winner Leon Lederman in jest in a speech. He subsequently used it in the title of one of his books (Lederman & Teresi, 1993). The term was then picked up by the press and has managed to survive all attempts by physicists to replace it with its proper name, the Higgs boson. The particle is named after Peter Higgs, who predicted its existence in 1964 (Higgs, 1964). But more on that below.

Disclaimer 2: I will try to explain the theory behind the Higgs boson and the LHC without a lot of mysterious-looking equations full of Greek letters, but instead via more or less accurate analogies. The topics discussed here are at the forefront of current research, and our knowledge is still quite incomplete. The explanatory analogies are therefore necessarily incomplete as well and possibly flawed in one aspect or another, because microscopic quantum constituents do not always behave according to our macroscopic intuition. I am hoping to convey the main picture, but I am also hoping that the reader will not take every aspect and logical consequence of a particular analogy too literally[2]. Most of the analogies are mine, except where indicated, although similar ideas have been and are being used by others to illustrate the complex concepts of modern physics.

Now that we have these disclaimers out of the way, we can focus on the main topic: the discovery of a new particle, possibly the Higgs boson, and the important consequences of this discovery.

On July 5th, 2012, the front page of the New York Times read "Physicists Find Elusive Particle Seen as Key to Universe", following the big announcement about the potential discovery of the Higgs boson at the Large Hadron Collider (LHC). The official announcement was made on July 4th at CERN, the home of the LHC, in Geneva, Switzerland (CERN, 2012), after the physics blogosphere and other internet outlets had been buzzing with more or less accurate rumors for weeks. Physicists had been looking for this particle for nearly five decades, and since the discovery of the tau neutrino in 2000 it was the only particle predicted by the so-called Standard Model of particle physics that has not yet been discovered.

The Standard Model describes all ordinary matter in the universe and is therefore a key piece in our theoretical understanding of how the world works. One of the main reasons for the construction of the LHC was the search for the Higgs boson. It is hoped that its discovery will provide clues about another one of the other big unknowns in our current understanding of the universe, the so-called dark matter, which makes up nearly a quarter of the remainder of the universe's content. The LHC itself is currently the world's biggest machine and also home of the world's largest international scientific collaborations. It is the world's and possibly the universe's largest and coldest fridge and the most complex experiment ever built by mankind.

[2] or infer the existence of Bigfoot, who makes more than one appearance in the analogies that follow.

Due to all these superlatives and mysterious unknowns it is therefore no surprise that not only the somewhat nerdy crowd of particle physicists were bubbling with excitement, but also mainstream media outlets were overflowing with titles and buzzwords such as "[…] key to the Universe", "Higgs boson find could make light speed travel possible", " 'God Particle' discovered", "the holy grail of physics", and similar headlines that could have been taken straight out of a Hollywood science-fiction blockbuster. Reading all this, it can be difficult for the layperson to distinguish fact from fiction[3]. Below you'll see what the fuss is really all about.

I will begin by briefly explaining our current state of knowledge of the basic building blocks of the universe. I will give an overview over the current composition of the universe and over the Standard Model, which explains all ordinary matter and its interactions, and what we know about the stuff that makes up the rest of the universe. Then I will explain why it was necessary to build a huge collider such as the LHC, which is housed inside a tunnel with a circumference of 27 km (17 miles) underneath Switzerland and France, and why the discovery took so long. I will conclude with a brief summary and an outlook.

2 Our Current State of Knowledge

Our current state of knowledge of the universe can be summed up in three pictures (and a few additional words), shown below in figures 1-3.

2.1 The Universe

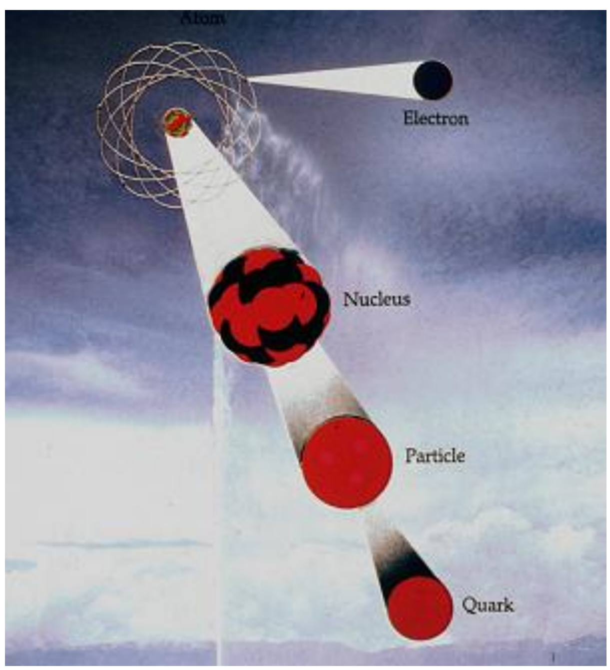

Figure 1: From atoms to quarks (CERN, 1993).

[3] Despite the perhaps somewhat sensationalist headlines, the mainstream media outlets provided for the most part factually accurate information in the body of their articles.

A bit more than a century ago, atoms were regarded as the basic building blocks of chemical elements and molecules. However, it turned out that each atom is composed of smaller building blocks: protons and neutrons form the core or nucleus of each atom, which is surrounded by an electron cloud, much like the sun is surrounded by planets in the solar system. Each proton and neutron in turn is composed of even smaller building blocks. These constituents, which we believe to be elementary at this point, are called quarks[4], and the quarks are bound together by so-called gluons[5]. Quarks and electrons along with a few more exotic relatives combine to form ordinary matter as we know it. These more exotic, very short-lived particles can be produced in cosmic rays or in high-energy colliders such as the LHC. Nevertheless, they all behave much like your run-of-the-mill protons, neutrons, and electrons and can be described by the Standard Model of elementary particles, which will be discussed in more detail in the next subsection.

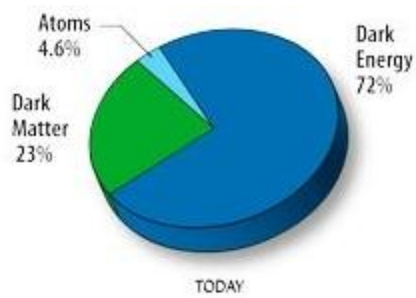

Figure 2: The current composition of the universe (NASA/WMAP Science Team, 2008).

Figure 2 illustrates the current composition of the universe as we understand it. As you can see, the ordinary matter that was the topic of the previous paragraph—atomic nuclei and their electron clouds, people and their gadgets, planets and their moons, solar systems and their suns, galaxies and dust clouds—only makes up about 4.6% of the universe.

About a quarter of the universe is made up of matter that we can't see, but that otherwise seems to behave like ordinary matter in terms of gravitational interactions. This matter is therefore referred to as "dark matter." Note that dark matter is not the same as ordinary matter that appears black. Ordinary black objects still exhibit the same interactions as other colored objects, they just do not emit any light (electromagnetic interactions) in the visible spectrum, but absorb light instead. Dark matter is different; it only interacts gravitationally (and perhaps via the weak interactions) with ordinary matter. A better name would be "invisible" or "transparent" matter. We can infer its existence with certainty from the gravitational influence it exerts on the ordinary matter surrounding it in space, and we can therefore conclude that it has mass. From the gravitational interaction with ordinary matter we can quite precisely infer how much dark matter there is in the universe and where it is located. Beyond that, the nature of dark matter is the

[4]Murray Gell-Mann, who postulated the existence of quarks, named them after a word in James Joyce's *Finnegans Wake*:
- Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark (Joyce, 1939).

[5]The etymology of the names of particles and phenomena in physics is certainly an interesting topic, especially for linguists, but such a discussion would fill a whole presentation all by itself. I will therefore have to refer you to a future presentation at another conference.

subject of much speculation. Many theories have been put forward, but concrete evidence for the correctness of any of these theories has yet to be found. It is hoped that the LHC will unearth evidence that may shed light on the nature of this dark matter—pun intended. This search combines the results of studies of the very large and the very small, that is, of astrophysics and of particle physics, respectively. A bit more on that below.

The third major component of the universe as we know it is even more mysterious, the so-called "dark energy." If you plug all the known mass of the universe, that is, the masses of ordinary and dark matter, into Einstein's equation of general relativity that describes the expansion of the universe, you come to the conclusion that the expansion of the universe must be slowing down. However, this is not what is observed when looking at the speed with which objects out in space recede away from us. We can measure quite precisely that the expansion of the universe accelerates. Therefore, there are two possible conclusions: Einstein was wrong, or there is an additional component in the universe that accelerates the expansion. It should be said that Einstein's theory of general relativity has been tested time and again, and aside from the slight problem with the expansion of the universe, all other experimental results agree to the umpteenth digit with the theory. In any case, in order to describe the expansion of the universe within general relativity you need an additional term in the equation to make the result agree with astronomical observations. Loosely speaking, this additional term is dubbed "dark energy." Whether this dark energy is "dark" or even remotely energy-like is anybody's guess and subject to even more speculation than dark matter. But the topic of dark energy is yet another presentation by itself. For the rest of this paper, let us return to the more ordinary content of the universe.

2.2 The Standard Model of Elementary Particles

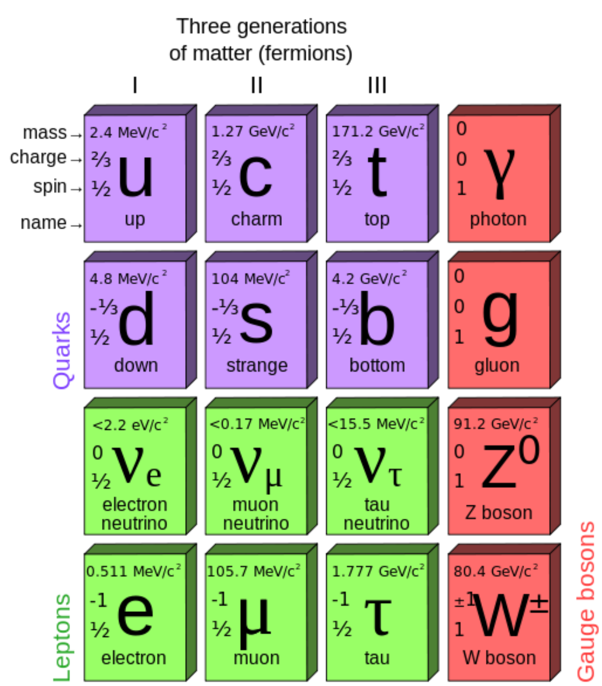

Figure 3: The Standard Model of particles
(Fermilab, Office of Science, United States Department of Energy, Particle Data Group, 2006).

Figure 3 sums up our current knowledge of the "ordinary" 4.6% of the universe: the Standard Model of elementary particles. As already mentioned above, ordinary atoms, and therefore you and me, are made up of protons and neutrans containing up and down quarks that are surrounded by electrons. The up and down quarks are shown in purple in the first column. The electron and its partner in crime, the electron neutrino, are shown in green in the first column. Neutrinos appear in certain types of radioactive decays, as nature's way to conserve energy and momentum in these decays[6]. The first column is replicated three times, that is, the up and down quarks have two pairs of siblings, the charm and strange quarks, and the top and bottom quarks, the latter was formerly also known as beauty. These other quarks are heavier than the up and down—their masses are stated (in some units appropriate to these microscopic particles) in the upper left-hand corners of the boxes representing the particles in the figure. Like the up and down, they also combine to form particles similar to protons and neutrons. These can be produced in the lab and are also produced all the time in cosmic rays and other astrophysical phenomena, but decay relatively quickly into their lighter and more stable counterparts, protons and neutrons. Electron and electron neutrino have two pairs of siblings as well, the muon and the muon neutrino, and the tau and the tau neutrino. The six particles are shown in green above and are collectively known as leptons.

These elementary matter particles interact via three types of forces besides gravity: electromagnetic, strong, and weak. The strong interaction is what binds quarks together in protons, neutrons and their relatives. The weak interaction is for example at play in radioactive decays. The electromagnetic interaction probably requires the least amount of explanation; we are all familiar with electromagnetic waves: visible light, microwaves, and radio waves are all examples from everyday life. Strong, weak, and electromagnetic interactions are all mediated by so-called gauge bosons, particles that act as the carriers of these forces. The photon (light-particle) mediates electromagnetism, the gluon the strong nuclear force, and the W and Z bosons the weak interaction. These are listed in the red column in Figure 3.

Matter particles and force carriers can be described by a unified quantum theoretical formulation which is known as the Standard Model of particle physics. The Standard Model predicted several of the quarks and leptons—the bottom, the top, and the tau neutrino—(long) before they were discovered and has otherwise been confirmed with overwhelming experimental and theoretical success. However, efforts to achieve a unified quantum theoretical description that also incorporates gravity and agrees with experimental observations have so far failed or are as yet incomplete. Nevertheless, it should be stressed again, that all experiments have confirmed the Standard Model with almost astonishing success. Therefore, even if some ingredients that will be presented below sound somewhat strange, they make perfect sense when tested experimentally.

Another issue that I have yet to mention is the question of mass. Connected to that is the final missing particle of the Standard Model, the Higgs, which, as the astute reader may have noticed, is not shown in Figure 3. But before we get to the Higgs, we need to discuss another mysterious notion: fields.

[6] The conservation of energy is one of the fundamental laws of physics that have prevailed even after the introduction of quantum theory, which contains all sorts of non-intuitive happenings, but (relativistic) energy is still conserved.

2.3 Fields

In the previous section you may have been somewhat puzzled by the fact that I mentioned several forms of electromagnetic *waves* as examples of the electromagnetic force, but two sentences later I wrote that this force is mediated by *particles*. Is it a wave or is it a particle? The answer to this question is that it is the wrong question to ask. At the beginning of the last century, physicists used to describe the properties of light either by assigning it a corpuscular nature or by treating it as a wave. Nowadays, in the formulation known as the Standard Model, electromagnetism, and all the other particles and force carries in Figure 3 are described by *fields*.

Now, what are these fields? The overly dry mathematical definition of a field reads as follows: a field is a physical quantity associated with each and every point in space and time. This definition inevitably conjures up the image of some mysterious "presence" filling out the entire universe, like the ancient and medieval concept of ether, a material thought to fill out the region of the universe above the terrestrial sphere. However, matter fields are quite localized in space and time, and there are well-defined equations that allow us to calculate their location and movement. The Anderson-Brout-Englert-Guralnik-Hagen-Higgs-Kibble-field[7], which we will discuss in the next subsection, is somewhat different. But first, we need to understand what a field is.

A field has a value everywhere at any time, but that value can be (and is for the most part for matter) Zero. Let's look at an example:

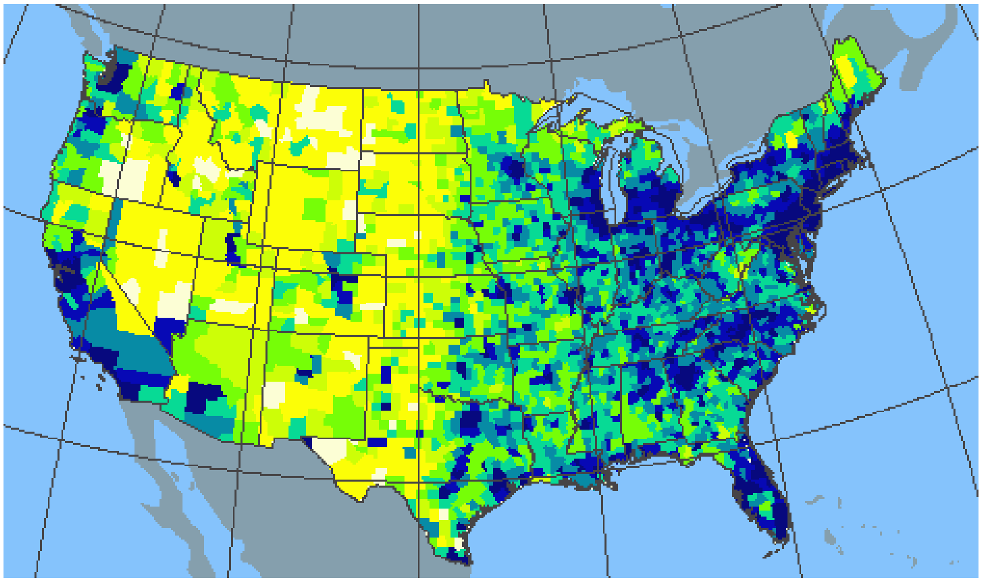

Figure 4: Population density map of the US, year 2000 (National Atlas of the United States, 2003).

[7]The mechanism referred to here that postulates this field was first proposed in 1962 by P. W. Anderson (Anderson, 1963) in a non-relativistic context, and then in 1964 further developed in a relativistic context by three independent groups: R. Brout and F. Englert (Englert & Brout, 1964); P. Higgs (Higgs, 1964); and G. Guralnik, C. R. Hagen, and T. Kibble (Guralnik, Hagen, & Kibble, 1964). P. Higgs worked out the details of the resulting particle, which is now named after him.

Figure 4 is a classic example of a 2-dimensional *field*. In this case, the field describes the population density in the year 2000 across the US. Darker regions denote more densely populated areas, and light regions are sparsely populated. Every point within the US on the map is colored, therefore every point in the US has an assigned value, and the quantity associated with the map-colors is the population density.

Let us look at another, related (hypothetical) example: the population density of bigfoot-creatures across the continental US. This population density field is illustrated in Figure 5 in two variants. Figure 5a) shows the purported general Bigfoot population density in the US, whereas Figure 5b) shows the density of purported bigfoot-creatures named Lucy. The general Bigfoot population density field is nonzero across most of the US, that is, it is not localized at one point in space (and time). In the latter case, however, the population density field of Bigfoot creatures named Lucy has a (highly speculative, unconfirmed) value of 1 (one Bigfoot named Lucy) in Ridgway, Pennsylvania in 2007, and 0 everywhere else. You see that even though you can assign a value to the Lucy Bigfoot population density field at any and all points in space and time, this does not mean that Lucy can exist simultaneously everywhere. On the contrary, Lucy is quite localized in space and time.

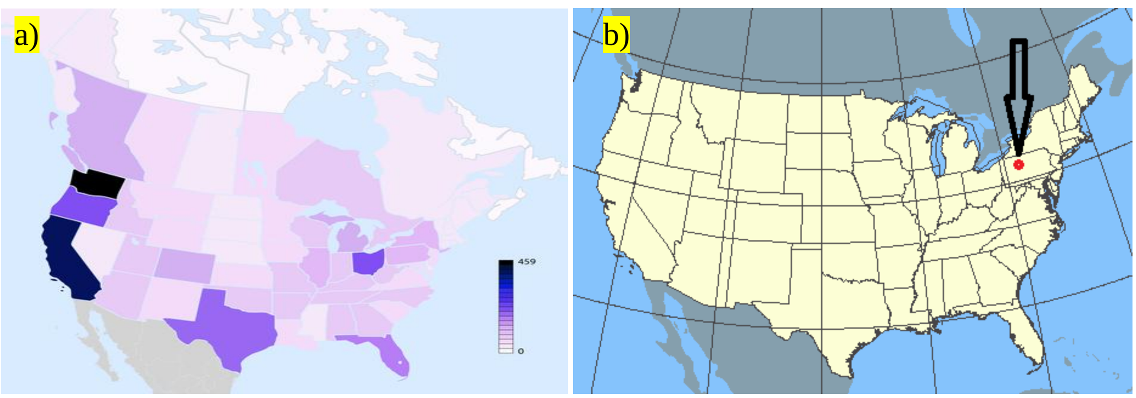

Figure 5: a) Hypothetical general population density of bigfoot-creatures in the US (User: Fiziker, 2008). Darker shades denote a higher number of purported Bigfoot-sightings, i.e. a higher population density.

b) Hypothetical population density of bigfoot-creatures named Lucy in the US, date ca. 2007. Red indicates a value of 1 for the population density, white indicates 0. The arrow is inserted for better readability.

Likewise, you can describe electromagnetism by a field, which has a value everywhere in space and time, but the fields describing *individual* particles have quite localized (within the region allowed by quantum mechanical uncertainty) nonzero values. In short, whether your field extends everywhere in space and time or whether your field has nonzero value only in a small localized region depends on which questions you are trying to answer—if you are asking about the location of a specific, individual particle, the corresponding field will have nonzero values only in a small space-time region. However, if you are asking questions about the general properties of particles, the corresponding fields extend through a wider region in space-time. And the Standard Model is the theory of all these quantum fields.

As an aside, the reason I am emphasizing this distinction between space-time-filling fields and more localized ones is that quantum field theory is sometimes hijacked in order to explain "paranormal" or similar phenomena. While I don't deny that there are phenomena out there that we cannot yet explain with our present knowledge or may well never be able to explain, this doesn’t mean that we should not try or instantly invoke some mysterious omnipresent quantum field that does not have any calculable consequences. The difference between some crackpot theory and a physical model is that the latter makes precisely calculable predictions (as opposed to postdictions) and therefore has verifiable or falsifiable consequences. Admittedly, a space-time-filling field such as the one that we will discuss in the next subsection may sound very much like a sci-fi phenomenon. However, it has very real, verifiable consequences, as we will see.

2.4 Masses and the Higgs

As already mentioned above, when you look closely at Figure 3, you will see little numbers written in the upper left-hand corners of the boxes that represent the particles. These numbers are the masses (rest masses, for the experts) of the respective particles, in some units appropriate for these minuscule particles. You can see that quarks and leptons all have mass, although the neutrinos are extremely light. The theoretical framework—the quantum field theory—that describes these particles and their interactions would work just as well if they were massless. Actually, and more correctly, it even requires the W and Z bosons, the force-carriers of the weak interaction, to be massless. However, they are anything but massless. It seems we have a problem.

The Higgs mechanism (or Anderson-Brout-Englert-Guralnik-Hagen-Higgs-Kibble-mechanism, see footnote 7) can be illustrated by a slightly modified analogy borrowed from David Walsh (Walsh, 1993). Imagine the conference room at the ATA Conference during a break. People are standing around randomly distributed in small groups talking to their nearest neighbors. Moving between people is easy, because everybody is distributed more or less evenly around the room. Bigfoot enters the room[8]. People are starting to cluster immediately around the strange visitor to get a better look and interact with Bigfoot. It becomes more and more difficult for Bigfoot to actually traverse the room due to all the people that are clustered around the creature. It effectively acquires a “mass” (a massive cloud of people) because it carries some sort of “Bigfoot celebrity charge” and everybody notices the creature. Now, imagine another, regular person traversing the same room. Naturally, with all the big fuss about Bigfoot, nobody notices, because the regular person carries no “Bigfoot charge.” Therefore, traversing the room without such a charge is easy and the person remains “massless.”

The situation regarding the Higgs field is quite analogous, albeit a bit more complicated mathematically. The Higgs field has a nonzero value throughout the entire universe; it fills the vacuum with a nonzero value. Particles move through this field like through some sort of space-time-filling jello and acquire a mass. More precisely, particles that couple via the weak interaction acquire a mass by interacting with this vacuum-filling field. This means that the quarks and leptons, as well as the W and Z bosons, all acquire masses by interacting with the Higgs field. These masses can be (and have been) calculated and measured. In addition, the Higgs particle itself acquires a mass, because it couples to its own field. Therefore, we have massive quarks, leptons, electroweak bosons, and the Higgs, whereas the photon and the gluons remain massless, since they only interact electromagnetically and strongly, respectively.

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[8] We are assuming that this Bigfoot is friendly. If people ran away in panic, the analogy would not work.

Now, all this may seem really far-fetched or just plain crazy, but the fact is, this is the minimal model that can explain all the particles and interactions that we have observed so far. And in fact, philosophically, it is not so crazy if you think about the notions of space-time and vacuum. Why shouldn’t the vacuum have a nonzero “charge”? Even more speculatively, perhaps the Higgs field is somehow connected to dark energy. In any case, the theory is at least mathematically correct, because theorists were able to predict not only the existence but also the precise mass of the W and Z bosons as well as the top quark (see Figure 3) long before they were discovered with precisely the predicted masses.

However, the Standard Model can’t be the whole story, since a viable theory of quantum gravity is still missing, and we have yet to discover the nature of the other 95% of the universe (see Figure 2). Nevertheless, despite all its successes and more or less universal acceptance among physicists as at least an effective theory of elementary particles[9], one major ingredient of the Standard Model was (or more precisely: is) yet to be discovered—the Higgs particle itself.

3 The Search for the Higgs

Although the existence of the Higgs boson was postulated more than four decades ago, its existence still remains to be proven. On July 4th of this year, CERN announced the discovery of a “Higgs-like” particle, but it remains to be seen whether it really is the Higgs or something else. So we built this huge machine and after more than four decades of searching we finally found something, but we’re still not sure that it’s actually the Higgs? An explanation of the inner workings of particle colliders is in order.

3.1 $E = mc^2$

You are all familiar with the (in)famous image showing Einstein’s face with his famous equation $E = mc^2$ written on a blackboard next to him. This equation very roughly means that energy E and mass m are equivalent—the details are a bit more complicated and the equation needs to be modified for particles that are moving around instead of being at rest, but that’s the gist of it. In other words, energy and mass can be converted into each other, whereby the square of the speed of light c functions as the conversion factor, much like you can convert Euros into Dollars at a certain exchange rate[10]. At particle colliders such as the LHC, collision energy is converted into mass, which manifests itself as particles that fly out of the collision region into the detectors. If the energy is high enough, these particles are hopefully new, unknown particles.

At the LHC, two beams containing protons are accelerated to very near the speed of light and then collided head-on in a circular tunnel with a circumference of about 17 miles underneath France and Switzerland. This large ring is necessary, because it costs energy to bend the paths of the beams away from a straight line without slowing them down. The larger the circumference,

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[9] The term effective theory is jargon for a theory that contains equations that are valid and correct in some range of application, but that is superseded by another, more complete theory that extends this range of application. An example is Newton’s theory of gravity, which works well with objects moving at speeds much slower than the speed of light, such as apples and baseballs. Einstein’s theory of general relativity extends Newton beyond this range to speeds close or equal to the speed of light, but precisely reduces to Newton’s equations in the nonrelativistic limit (at slow speeds).

[10] Unlike currency exchange rates the speed of light does not change over time, at least as far as we know.

the less bending is needed. The collider is circular, so that the beams can make many passes and thereby increase the distance during which they are accelerated, because the higher their speed, the higher the resulting collision energy. Powerful superconducting magnets are necessary to bend the fast-moving beams. These superconductors require very low temperatures, very close to absolute zero, and the cooldown procedure of the machine, facilitated by 96 tons of liquid helium, takes almost a whole month. Four huge detectors around the ring—the largest of them 82 feet (25 meters) in diameter—collect the data resulting from the collisions.

In these collisions, as already alluded to above, the energy resulting from the collision of two protons in the beam is converted into matter. The resulting particles then fly outwards through these huge detectors, where they decay further. The decay products leave tracks that result in electronic impulses, which are pre-analyzed, stored, and subsequently transmitted to many computing centers around the globe forming a computing network called the Grid, where the data is analyzed further. Since there are many protons per beam, and since the beams travel at 99.9999991% the speed of light and therefore circle around the ring 11,245 times per second, about 600 million collisions take place every second. The recorded data could fill the equivalent of 100,000 dual layer DVDs every year (CERN Web Communications, 2008). That is a lot of data. Still, with the computing power on the Grid, that doesn't sound so bad. The LHC has been colliding protons and collecting data since November 2009. If there are 600 million collisions per second, why hasn't the new Higgs candidate been found sooner? And why are scientists still not sure whether it's the Higgs?

3.2 What's Taking So Long?

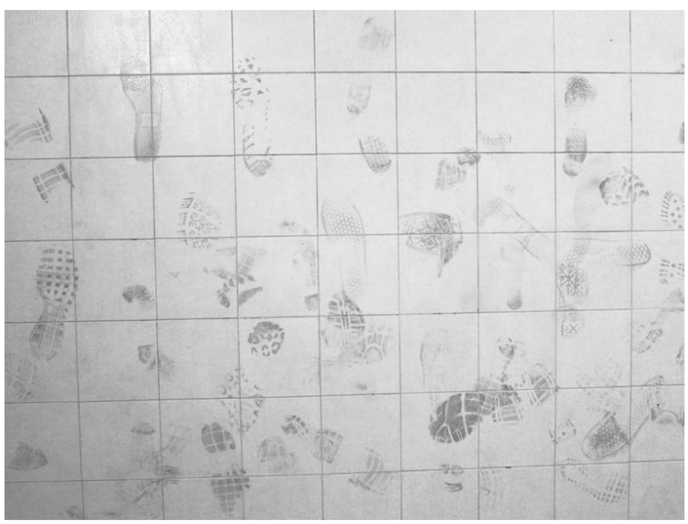

Figure 6: Were any of these shoeprints left by Bigfoot? Image source: (Martingraf, 2012)

Imagine a group of crime scene investigators (CSIs) trying to figure out from a set of shoeprints whether these shoeprints were left by Bigfoot or whether these shoeprints were left by a human being of equal height and weight. Of course, that would be easy if Bigfoot hadn't purchased some sneakers to disguise his paw-prints. But that's not the only complication for our CSIs. The CSIs have to pick the relevant shoeprints out of a multitude of other shoeprints left by other people on the scene. Nevertheless, the CSIs are confident that they can infer whether the prints fall into the right height and weight range to potentially have been left by Bigfoot by extracting and analyzing the prints one by one.

But how can the CSIs definitively conclude that a Bigfoot shoeprint candidate actually stems from Bigfoot? While some of the shoeprints might have been left by Bigfoot, some of the other shoeprints could have been left by humans of similar stature to Bigfoot. The CSIs have additional information: they know precisely how many human beings of a stature similar to Bigfoot there are, and how many of them walked through the area with the footprints they are analyzing. Therefore, if they see more shoeprints than these humans could have left, they have strong evidence for the existence of a non-human creature with two legs. Further analysis via laser-imaging and computer simulations reveals the exact ratio of leg-length to torso as well as precise height and weight of this creature. From this information they are able to construct a three-dimensional model of the creature, which, lo and behold, looks indeed very much like Bigfoot.

At the LHC, protons are collided at nearly the speed of light and the resulting collision energy is converted into particles, because according to Einstein, energy is equivalent to mass. If the energy is high enough, new particles with higher masses are produced. And even though there are many collisions taking place every second, one might think that it's just a matter of carefully looking through the events with the help of the super-microscopes called detectors to pick out the right one that contains a Higgs. Unfortunately, it's not so simple. In fact, the situation at the LHC (and its meanwhile defunct predecessor, the Tevatron collider at Fermilab in Batavia, IL, USA) is very similar to our CSI shoeprint analogy.

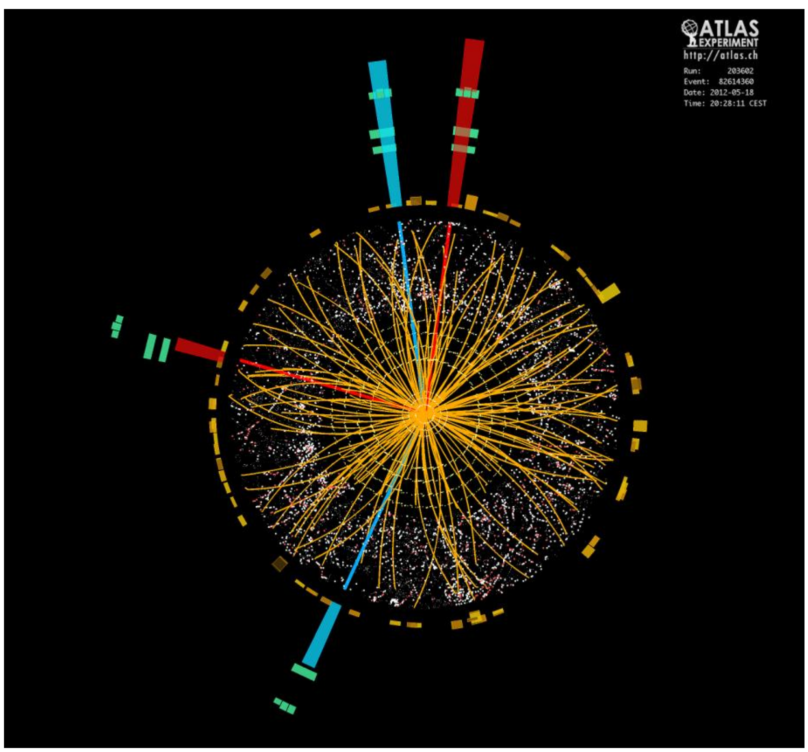

Figure 7: Event display of a Higgs to 4 e candidate event (ATLAS Collaboration, 2012).
The event was recorded by ATLAS on 18-May-2012, 20:28:11 CEST in run number 203602 as event number 82614360.
The tracks and clusters of the two electron pairs are colored red and blue, respectively.

Figure 7 shows an already processed (and colored!) event recording. As you can see, there are many particles in this collision that leave tracks (yellow, blue, and red) in the detector. The raw data don't come colored like that out of the detector, so you can see that even this quite clean event looks like a mess. Aside from the primary collision products (red and blue tracks), there are many secondary products (the yellow tracks) that stem from secondary collisions or are radiated by the primary collision products. In addition, neither of the primary collision products is the Higgs, because it decays nearly instantly. In fact, neither of the "primary" collision products that leave the tracks that you see in Figure 7 are the direct decay products of the Higgs, but rather the *decay products of the decay products!* The event that's shown in the figure is actually,

$$p + p \rightarrow H \rightarrow Z + Z,$$
$$Z \rightarrow e^{+} + e^{-}.$$

In words, two protons collide, produce a Higgs, the Higgs decays into two Z bosons (see Figure 3), which each decay into an electron and its antiparticle, a positron. Each of these decays happens nearly instantaneously, such that neither the Higgs nor the Zs can travel far enough in the detector to leave their own tracks. Instead, all you see is a collision point where two electron-positron tracks originate. These tracks are surrounded by a big mess of secondary tracks. How can you figure out which particles left these tracks in the detector?

Each detector consists of several thick layers of various materials and is surrounded by a magnetic field. Each particle type's path is curved slightly differently in this magnetic field, depending on the particle's mass and charge. Furthermore, each particle type interacts differently with the different layers of the detector, such that the species of the particle that left a specific track can be determined fairly accurately.

But there is one more complication for the LHC scientists: there are other particles in the Standard Model that decay into the exact same final state, and these impostor-particles are produced millions of times more often than the Higgs in proton-proton collisions. That is, only one event out of millions of events with the same 4-electron-final state stems from the Higgs, the rest are all produced by decays of other, known Standard Model particles. So you do not only have to wait until such a rare Higgs is produced, you also need to sift through millions of events that look almost exactly like it. These other events are referred to as background. The search for the Higgs is therefore often referred to as the proverbial search for a needle in a haystack. A better analogy would be the search for a needle in a haystack of many comparable needles.

However, just like our CSIs above, we have more information than just the tracks shown in Figure 7. We know all the other particles that can produce the same decay products as the Higgs really well, and we can calculate precisely how these decay products should behave. We know precisely how many of these background decays into two electron-positron pairs we can expect, and we can calculate how many decays we can expect from the Higgs. If there is an excess of observed events over the expected background, we have a signal. Due to the rare nature of the sought-after events, statistics comes into play here, and it is simply a matter of time and patience to collect enough data to be able to make a definite statement about whether a small blip in a graph that rises above the background curve is a statistical fluctuation or the result of a real particle. Last year, a small blip in excess of the background was seen, but there was not enough data to rule out a statistical fluctuation. On July 4th of this year, enough data was collected to be able to make the definite statement that there is a new particle decaying the same way as if it were the Higgs. But is it really the Higgs?

The measured signal behaves slightly differently from the background in terms of spatial distribution of the track in the detector and in terms of other measured properties. A careful analysis of these distributions should confirm within the next few months whether the discovered particle really is the Higgs, or some impostor. Many physicists actually hope for the latter. That sounds quite counterproductive. After all, the Higgs was predicted nearly 50 years ago, and it would be a triumph for both theory and experiment if it were discovered unambiguously. But there is still the small problem that the Standard Model only accounts for less than 5% of the universe's content.

3.3 The Higgs as a Portal to Dark Matter?

Imagine you are sitting in a valley surrounded by high a mountain range, in the pre-electronic-communications era. You have heard strong rumors that a horde of bigfoot-creatures is living in an adjacent valley, but the only ways to verify their existence is to either climb over the very high mountain into the other valley or to dig a tunnel through it. The zoologists in your village have a variety of theories about the bigfoot-species, however, without studying a real live specimen, it is impossible to confirm or disprove these theories.

We are in a similar situation when studying dark matter, which, as already mentioned in the previous chapter, makes up nearly a quarter of the universe's content. Dark matter does not interact electromagnetically, but it is theorized that it could interact via the weak interaction, which, as the name says, is too weak, and its range is too short for us to measure it out in space, where the dark matter is "hiding." Therefore, there are two options for us to study dark matter: either we produce it directly in the lab, or we study it indirectly via its influence on ordinary matter.

Let us discuss the first option. All of the theories that hope to explain dark matter and how it is connected to ordinary matter contain a host of additional particles: the "dark" particles that are invisible to us, as well as particles that are too heavy to have as yet been produced in a collider on earth, but which decay subsequently into ordinary matter and/or dark matter. Therefore, in order to directly produce dark matter, we must first produce new, heavier particles that decay into dark matter. In other words, we must climb over the mountain to be able to descend into the other valley. If the newly discovered particle is not the Higgs, it could be one of those new, heavier particles, and dark matter may be hiding among its decay products. These decays could be very rare, which explains why we haven't discovered them yet.

The other option to study dark matter is to study its influence on ordinary matter, more precisely, on the Higgs particle, if the newly discovered particle is indeed the Higgs. Since the Higgs mechanism is responsible for giving particles mass, and since dark matter has mass, dark matter must necessarily interact with the Higgs and slightly alter its properties. But these altered properties are visible to us and can therefore in principle be studied. In other words, we need to build a tunnel, or portal, to the dark side. However, since the possible visible effects of dark matter are very small, much more data and very careful analyses are needed.

3.4 Black Holes at the LHC

I conclude this paper with a brief side remark about black holes, since I promised a discussion of this topic in the title. In 2008, a civil lawsuit was filed in Hawaii's U.S. District Court (of all places!) against the US Department of Energy, the National Science Foundation, Fermilab, and CERN itself, trying to prevent the startup of the LHC out of concern that micro black holes could be produced at the LHC which might grow and swallow the earth. An official investigation concluded that the experiments at the LHC pose no risk and the lawsuit was dropped.

In brief, the argument goes as follows. First, black holes that arise when stars collapse, are macroscopic, that is, much larger than anything the LHC could ever produce. The energies of potential micro black holes at the LHC, if they could be produced at all, would be equivalent to the energy of a mosquito. These micro black holes are therefore not big enough to be stable, and one can calculate unambiguously that they would decay almost immediately. Second, the LHC does not do anything that does not constantly happen in cosmic rays, where particles collide at partially much higher energies than can ever be produced on earth. Parts of these cosmic rays pass near or even through the earth and have done so ever since the formation of our solar system. If these rays contained anything dangerous, the earth would have been destroyed long ago. A more detailed reasoning can be found on the CERN website and links therein (CERN Web Communications, 2008).

4 Summary and Outlook

Above, I have given some background information about the particle that was newly discovered this year at the Large Hadron Collider at CERN. I reviewed what we know about the universe and its content, gave a brief overview over the current Standard Model of elementary particles, and explained in some detail the importance of the Higgs particle for our understanding of the origin of mass. A whole section was dedicated to the complex experiments that led to the discovery of this new particle.

At the time of writing (August 2012), it is still unclear whether the new particle is indeed the long-sought Higgs boson or some other, even more mysterious particle. In the talk I will show actual data and give an update on the latest experimental results. Perhaps we will know more by then. Stay tuned!

5 References and Further Reading

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Further Reading

There exist a variety of popular science books on the topic for every taste. You can find a selection in every good bookstore or online for your e-reader. Here I would like to recommend some of my favorite not-so-well-known online sources:

- http://www.quantumdiaries.org/ — A collection of blog posts by physicists working on the LHC. The posts range from introductory to quite technical, and not all of them are written in English, but in the scientists' native languages instead.
- http://www.particleadventure.org/ — An award-winning online exposé on particle physics by the Particle Data Group at LBNL.
- Tait, T. (2012). *Why Look for the Higgs?* http://www.youtube.com/watch?v=sqrwtQcrNBI —Semi-technical lecture given at SLAC, June 18, 2012.